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Molecular lines studies at redshift greater than 1

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Abstract. Observations of CO molecules in the millimetrer domain at high redshift (larger than 1), have provided interesting informations about star formation efficiency, and its evolution with redshift. Due to the difficulty of the detections, selection effects are important. The detection if often due to gravitational amplification. Objects selected by their (far)infrared flux, are in general associated to ULIRGS, mergers with starburst in the nuclear regions. Quasars have been selected as powerful optical sources, and have been found to be associated to starbursts, rich in gas. The gas fraction appears to be much higher at redshift greater than 1. Quasars allow to probe the end of the reionisation period, and the relation between bulge and black hole mass. However these selection bias could have led us to miss some gaseous galaxies, with low-efficiency of star formation, such as the more quiescent objects selected by their BzK colors at z=1.5 or 2.

Keywords. Galaxy, molecules, high redshift, star formation, quasars

1. Introduction

Up to 2009, there is about 50 high redshift sources detected in the CO lines. This domain of research has grown quickly, from the first discovery in 1992, of the faint IRAS source F10214+4724 at=2.3 (Brown & van den Bout 1992, Solomon et al 1992). Most of the sources have a redshift between z=2 and 3. Recently, Iono et al (2009) observed 30 of these sources homogeneously in CO(3-2) with SMA, and found a very good correlation between CO and FIR luminosities, even for QSO. This means that, although the contribution of the AGN to the FIR luminosity increases with power, the starburst always dominate.

The advantage to detect the CO lines, is to obtain the efficiency of star formation (ratio of FIR luminosity to the gas content), which evolves quickly with redshift, and when resolved, study the kinematics and mass at high z: for example, the source SMM J2399-0136 at z=2.808, has been spatially resolved with the IRAM interferometer, and a hint of rotation curve has been found at z=2.808 (Genzel et al 2003). Taking into account the lens amplification factor of 2.5, the H_2 mass derived is 6 10^{10} $M_\odot$, and the dynamical mass is 3.0 $10^{11}/\sin^2 i$ $M_\odot$, uncertain, since the inclination of the object is not well determined.

2. Recent results

Thanks to strong gravitational amplification, it was possible to detect CO line emission towards 6 quasars at z larger than 4, and determine their surprising properties.

The most distant quasar detected, SDSS J1148+5251 at z=6.4, is a unique object, at the end of the epoch of reionization. The Gunn-Peterson trough is detected in HI absorption in its spectrum (Fan et al 2003, White et al 2003). In this powerful starburst, of surface density 1000 $M_\odot$/year /kpc^2, an impressive list of molecules has been detected,

and even ionised carbon CII (158μm redshifted at 1mm), cf Walter et al (2009). Surprisingly the HCN molecule is not detected, while HCN is the better tracer of star formation, well correlated with FIR (Gao & Solomon 2004).

One of the common features of the z>4 quasars, resolved in the CO(2-1) line with the VLA, is that they are gas-rich mergers of galaxies, with complex morphologies, and molecular extent of about 5kpc, much larger than local ULIRGs (Riechers et al 2008a,b). Once corrected for their strong amplification, their H_2 mass is up to 10^{11} $M_\odot$, a significant fraction of the dynamical mass. although the latter is ill-defined, given the perturbed shapes. Their black hole masses, derived assuming their AGN radiate at Eddington luminosity, or from the nuclear emission lines, appear an order of magnitude higher than expected from the Magorian relation. But uncertainties are large.

Their star formation surface density is saturating around 1000 $M_\odot$/year /kpc^2, as for Eddington limited star formation, i.e. dust opacity limited gas surface density. The average H_2 column density reaches 10^{24} cm^{-2}, and the volumic density 10^4 cm^{-3}.

Objects at more moderate SFR are not detected, unless strongly amplified. Three Lyman-break galaxies (LBG) at z$\sim$ 3, such as the Cosmic eye (Coppin et al 2007) with a magnification of $\sim$ 30, also satisfy the same FIR-CO luminosity relation. Their star formation rate is of the order of 50 $M_\odot$/year, with a starburst time-scale of 40Myr, they are the high-z analog of local LIRGs.

The most efficient star forming objects appear to be the Submillimeter Galaxies (SMG), which have been selected by their FIR luminosity, redshifted in the mm. They are more efficient than ULIRGs, and are very compact starbursts, of radius lower than 1kpc, or less. But all detected objects at high z are not so efficient. Recently, the BzK galaxies, selected for their red colors, have been detected with much more CO emission than expected, at z=1.5-2 (Daddi et al 2008). These are also ULIRGs, but with a much larger molecular content, and a time-scale to consume their gas of $\sim$ 2 Gyr. They are extended 10kpc disks, and their CO excitation is low, peaking at CO(3-2) like the Milky Way. Another star forming BzK galaxy however was not detected by Hatsujade et al (2009), and certainly, they have a wide range of properties. Due to their low excitation, it might be appropriate to use a higher CO-to-H_2 conversion ratio than for ULIRGs (Dannerbauer et al 2009).

SMG are much more concentrated, more compact, they are expected to be major mergers remnants, with low angular momentum, and precursors of elliptical galaxies (Bouche et al 2007). Do they actually trace massive haloes? In the GOODS-N field, a cluster of radio galaxies and SMG at z=1.99 has been studied, it is the strongest known association of SMG (Chapman et al 2008), with an overdensity of 10. SMG appear also to be associated to filaments traced by Lyman alpha emitters (LAE). In SSA22, a protocluster region at z=3.1, traces a filament, where SMG have been detected at 1.1mm with AzTEC on ASTE (Tamura et al 2009).

SMG are also sometimes associated to another type of objects, Lyman-alpha blobs (LAB, Geach et al 2007), huge ionised gas nebulae, excited by a central starburst or AGN. In local clusters at z=0.4-1, such as CL0024+16, the LIRGs detected by Spitzer at 24μm can be detected in CO (Geach et al 2009).

The fact that at high redshift, most detected objects are quasars, allows to study the AGN-starbutst association, and possible AGN feedback on CO emission. For instance, APM08279+5255 at z=3.9 is a lensed QSO, (amplification factor 50), and one of the brightest object in the sky; it has been observed with mm and cm telescopes, the CO lines from CO(1-0) to CO(11-10) are detected. Recent 0.3" resolution CO(1-0) mapping with the VLA (Riechers et al 2009), reveals that the emission is not extended, as previously thought. The amplification factor could also be lower. The CO line emission is co-spatial

with optical/NIR and X-rays, and very compact. The best model shows that the CO is in a circumnuclear disk of 550 pc radius, inclined by 25°, with a gas mass of 1.3 10^{11} $M_\odot$. There is no hint of the influence of the AGN feedback.

3. Perspectives

About 50 systems are presently detected in molecular lines at high redshift. Given the different properties of the various categories of objects, it becomes obvious that results are dominated by selection effects. ULIRGs have a very efficient star formation, their molecular gas has a compact distribution, and is highly excited. But BzK objects have much more extended gas, with normal star formation efficiency and consumption time-scales.

Present results are also strongly biased by lensing magnification.

One of the main robust results, is that quasars and starbursts are intimately linked, and the AGN activity does not seem to quench star formation, at these redshifts.

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